TEN YEARS OF EVAPORATION IN THE SOUTHWEST

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Theories as to the rate of evaporation and the elements that cause or promote it have been multiplied through the years. Beginning as early as 1670, British scientists were formulating theories of evaporation, and in 1687 Edwin Halley gave a paper before the Royal Society wherein he estimated the quantity of vapor (evaporation) raised out of the sea by the heat of the sun. And calculations were given as to the probable amount of evaporation from the Mediterranean Sea in a summer day. The accelerating influence of wind on evaporation was observed. Others followed on down to John Dalton, who may be called "the father of the science."

As early as 1793 Dalton published in London an essay in which he set forth the process and circumstances promoting evaporation—heat, dry air, and decreasing pressure of the atmosphere upon the evaporating surface are emphasized. In his experiments the rate of evaporation from water pretty well exposed to the sun and wind never exceeded 0.2 inch daily. In 1801 Dalton published his new theory of the constitution of mixed aeriform fluids and particularly of the atmosphere. Again in 1802 Dalton, in his experimental essays says:

> The objects are:
> 1. To determine the effect of temperature upon the rate of evaporation.
> 2. To determine the relative evaporation of different fluids.
> 3. To find a rule for ascertaining the quantity and effect of water vapor previously in the air.
> 4. From these and other facts to obtain a true theory of evaporation.

Out of this came the Dalton formula.

And down through the years the problems of evaporation have continued to develop many items and articles of interest. The experiments of Prof. F. H. Bigelow[1] at Reno, Nev., and at Salton Sea, Calif., tended to show that pans for evaporation that were buried in the ground would absorb too much heat from the soil and therefore show a greater evaporation than that which was obtained from simultaneous observations from pans floated upon the surface of water near by. This occurred in observations at Hemiston, Oreg., and Granite Reef, Ariz. On the other hand, Professor Carpenter, in experiments at Fort Collins, Colo., apparently met with the reverse condition and found both temperature and evaporation less from ground pans than from those which were obtained in near-by lakes or reservoirs and increased his figures accordingly. A like condition was obtained at Croton Reservoir, near New York City, and the figures from early observations at the New Mexico Agricultural College appear to conform to this and to confirm it when compared with data from Lake Avalon and Fort Bliss.

In theory, it would seem as if records which were obtained from pans floated upon the waters of a reservoir should show more nearly the correct evaporation than those which were obtained from pans buried in the ground near by or from those placed above the ground near by. Despite theory and the conclusions of Professor Bigelow, the standard finally adopted by the Weather Bureau consists of a 4-foot galvanized iron pan, 10 inches in depth, exposed on an open platform of spaced 2 by 4 timbers, raised slightly above the ground for circulation of air all round the pan, a still well and hook gauge, and, near by, a cotton region shelter with maximum and minimum thermometers, rain gauge and anemometer, the latter exposed beside and just above the tank. Just why this pattern was adopted I do not know, but it affords a uniform equipment, and the records should be in fair accord. I hope, therefore, that the following observations will prove interesting and that in time they will aid in securing a suitable formula to approximate evaporation at any station when the elements which enter into evaporation are known—insolation, temperature, precipitation, humidity, vapor pressure, wind movement, and probably barometric pressure, although I believe that too much stress has been placed upon barometric pressure by some of the investigators who conclude that evaporation is greater in the high altitudes because of the dryness and the reduced air pressure. Thus Hann says (Climatology, pp. 290–291):

> Under similar conditions of relative humidity, temperature, and wind velocity, evaporation is much greater on mountains than at lower levels because of the diminished pressure aloft. Everything dries much more rapidly at great altitudes. * * * The relative humidity alone is, therefore, no sufficient criterion for the evaporating powers of a mountain climate, the diminished pressure making it possible for the water vapor which has been formed to be distributed much more rapidly through the air, and hence evaporation is accelerated.

However, those of us who live in the higher regions of the Southwest know from daily experience of the increased precipitation and humidity, the cooler air, and the comparatively quiet wind movement that obtains, and the records thus far show evaporation considerably less than that obtained at near-by lower stations.

Investigators have also lamented the lack of uniformity in evaporation observations, the lack of uniform equipment, and the lack of a common interest, and a definite goal. Thus Hann says: "It is, unfortunately, a difficult matter to make observations of evaporation which shall be strictly comparable. In order to carry out such measurements it would be advisable to use evaporimeters which are precisely alike and to expose them in exactly the same way. But," he concludes, "even the amount of evaporation from a perfectly free water surface under sunshine is uncertain, because this depends also upon the depth, extent, and temperature of the body of water, and upon many other local causes."

It will thus be apparent, as we proceed, why so great variation appears in the comparatively limited area under consideration.

Weather Bureau evaporation stations began to operate in 1916, so that we have approximately 10 years of fairly complete records for consideration and comparison from the dozen stations in Texas, New Mexico, and Arizona.

The station at Santa Fe was placed in operation in May, 1916, and has been in continuous operation since. I mention this because many of the stations in the North and East do not undertake winter readings. The results show an average annual evaporation of 64.707 inches. The year 1917, which was the driest during the period, gave the largest evaporation, 75.815 inches, while 1919, the wettest, gave the lowest, 56.397 inches. The year 1917 was much warmer and drier and more windy than usual, while, on the other hand, the year 1919 was cool, quiet, and wet. The former represents a year with maximum evaporation and the latter a year with minimum.

The march through the year begins with a minimum in December, which averages 1.393 inches, and increases

[1] MONTHLY WEATHER REVIEW: July, 1907, 35:311-316; February, 1908, 36:24-39; Annual Summary, 1908; 36:437-445; February, 1910, 38:307-316; July, 1910, 38:1133-1135.

slowly in January, February, and March, while more or less ice obstructs the pan, but jumps (almost doubles) in April, with the increasing warmth and wind, going up rapidly until it reaches the maximum of the year in June, and going steadily downward thereafter to the minimum in December. The greatest monthly amount measured during the period was 11.989 inches in June, 1924, although almost as large an amount was measured in June, 1916, and June, 1917. The greatest heat of the year occurs in July, but it is also the wettest month of the year and much less windy than June; hence the greater evaporation in the latter month.

An interesting side light is cast upon the evaporation of the station and of the Southwest by a comparison of the actual results with the theoretical values given by Prof. Thomas Russell in the MONTHLY WEATHER REVIEW in 1888 (p. 239). He places the figure for Santa Fe at 79.8 inches, apparently having given too high value to the effect of altitude and, in theory, the drier atmosphere due to this factor.

TABLE 1.—*Estimated evaporation*

[Inches]

Station	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Fort Davis	5.4	5.7	6.7	8.5	11.0	12.0	11.4	9.0	5.9	5.2	5.7	4.9	96.4
Fort Stanton	3.9	3.9	5.2	7.3	9.5	10.9	9.4	11.6	3.9	4.0	3.6	3.8	76.0
El Paso	4.0	3.9	6.0	8.4	10.7	13.6	9.4	7.7	5.6	5.2	4.6	2.9	82.0
Santa Fe	3.0	3.4	4.2	6.8	8.8	12.9	9.2	9.8	6.6	6.7	5.7	2.7	79.8
Fort Apache	2.6	3.0	3.6	6.8	9.4	9.1	7.1	6.7	5.3	5.2	4.1	2.6	65.5
Fort Grant	5.2	4.8	6.4	9.2	10.2	13.8	12.4	10.5	9.0	7.9	7.2	4.6	101.2
Prescott	1.4	2.8	3.6	5.4	6.2	8.1	6.6	6.5	4.7	4.9	3.6	2.2	56.0
Yuma	4.4	5.2	6.6	9.6	9.6	12.6	11.0	10.2	8.2	8.2	5.5	4.6	95.7

I will content myself in this paper with a rather close survey of the data from the agricultural college and a more general and brief survey of the others in the group.

The agricultural college was made a standard station in September, 1918, hence has an eight-year record, and this is complete for temperature, precipitation, wind velocity, humidity, vapor pressure, dew point, and the resulting evaporation. I have not included the wet and dry readings nor the results to be obtained from them in the summary table. As at Santa Fe, so also at this station the lowest of the year occurs in December and the highest in June, with, however, a more uniform ascent and decline, since the season of ice is much shorter and accordingly much less troublesome. The annual average is 88.254 inches. The average monthly minimum is 2.520 inches in December and the average monthly maximum 11.906 in June, when clear skies, heat, dryness, and wind combine to give the largest evaporation. The maximum yearly record was 98.014 inches in 1922 and the minimum 75.566 in 1926, the latter a quiet, cool, wet year.

Within the State of New Mexico the greatest evaporation is apparently at the Elephant Butte Dam station. The pan here is placed on the bank of the lake about 100 feet above the water and is very freely exposed to the winds. The annual average is 100.617 inches, with a maximum of 109.692 inches in 1917 and a minimum of 84.247 inches in 1926, the former a dry, hot, windy year and the latter a wet, cool, and comparatively quiet one.

One of the interesting comparisons made possible by the dry years 1924–25 and the consequent emptying of Lake Avalon is that of the floating pan which for several years had been exposed in the spillway basin of the lake, but, because of the dryness and lack of water, was removed to the land adjacent. The annual average, as shown by the floating pan, is about 75.250 inches, but with the placing of the pan upon the land it at once jumped to 112.850 inches for the year 1925, and would probably have exceeded 100 inches for the year 1926 if the record could have been kept for the entire year. A brief record from a floating pan at Santa Fe, taken by the State engineer some years ago, showed an annual average of 59.370 inches. A similar record at Fort Bliss (from a pan on the Rio Grande) gave 85.910 inches, another at Elephant Butte gave 86.950 inches, and a sunken pan at the agricultural college gave 67.640 inches. On the other hand open pans at Carlsbad, N. Mex., and Granite Reef, Ariz., gave 107.250 and 115.180 inches, respectively.

On the plains a station at Spur, Dickens County, Tex., in a record from 1922 to 1926, inclusive, shows an annual average of 64.902 inches, with a maximum of 71.763 inches in 1922 and a minimum of 53.175 inches in 1926. The highest monthly record during the period was 10.923 inches in July, 1922, and the lowest 1.522 inches in December, 1926. The average for this station seems low, but may be accounted for by increased rainfall. However, a sunken pan station at the experiment farm near Tucumcari, N. Mex., although having records for the growing season only (April to September), seems to show a much larger average, due to the high winds of the plains country. And at this station a maximum monthly record of 12.380 inches was noted in July, 1922.

In mid-west Texas, at Hill's ranch, the annual evaporation averages 66.565 inches, with a maximum yearly amount of 80.447 inches in 1917 and a minimum yearly amount of 60.422 inches in 1926. The highest monthly record was 12.335 inches in July, 1918, and the lowest 1.838 inches in December, 1926.

A third station in Texas, Beeville, is on the coast and, while not in the Soutwest proper, is interesting as showing the reduction due to increase in precipitation, for temperatures are high at the station and the wind movement is the greatest of any of the stations under consideration. This station shows an annual average of 60.683 inches, with a maximum of 67.541 inches in 1925 and a minimum of 53.652 in 1926.

In Arizona six stations have been maintained. Lee's ferry, on the north bank of the Colorado River, has but one complete year of record during the period.

The station at Roosevelt, by the side of the lake, shows an annual average of 84.004 inches; highest yearly, 94.642 inches in 1917; lowest yearly 82.421 in 1920; highest monthly, 13.720 inches in June, 1921; lowest monthly, 1.496 in December, 1926, a month with 4.70 inches precipitation.

The Mesa experiment station, in the center of the State, shows an annual average of only 77.356 inches, due, probably, to the exposure of the pan in a field of alfalfa; highest yearly 88.905 inches in 1921; lowest yearly 66.951 in 1926; highest monthly 12.822 inches in June, 1921; lowest monthly 1.792 inches in January, 1917, a month with light winds, much precipitation and cool weather.

Wilcox, in the southeast part of Arizona, shows an annual average of 91.701 inches; highest 105.545 inches in 1924; lowest 83.441 inches in 1919; highest monthly 13.943 inches in June, 1917; lowest 2.567 in January, 1917, the latter a wet, cool, and rather quiet month.

The Yuma citrus station, an exposure southwest of the city of Yuma on the bare mesa, shows an annual average of 121.608 inches; highest 135.688 inches in 1921; lowest 111.300 in 1926; highest monthly 20.363 inches in July, 1924; lowest 2.960 inches in December, 1926, a cool, quiet, and wet month. And, finally, the Yuma evaporation station on the mesa near to the city, with the pan exposed in a field of alfalfa. This shows an annual average of 76.557 inches; highest 87.992 inches in 1918, lowest 70.303 inches in 1920; highest monthly 13.841 inches in June, 1918; lowest 1.971 inches in December, 1922.

It is evident, from the figures which have been given, that exposure has much to do with the resulting evaporation. The remarkable difference shown between the Yuma citrus and the Yuma evaporation stations proves this beyond a doubt, so that it is a great question if the stations for which I have presented data are, after all comparable one with another. But with the elimination of the Mesa experiment station and the Yuma evaporation station, where the exposures are in fields of alfalfa, the remainder appear in fair accord, greater wind velocity accounting for the higher evaporation at the Elephant Butte Dam, over the record for the agricultural college, which is equally warm and dry.

The real practical value of all this lies in the knowledge of the loss from ditches, streams, reservoirs, lakes, etc., to irrigation and the effect upon crops and soils. Davis, in discussing the loss to reservoirs near Phoenix, suggests reducing this loss by covering the surface of the water with a film of crude oil, a plan adopted by the users of "wet" cell batteries many years since. And Professor Hoffman considers it important in a dry climate to keep the soil covered with moss or dead leaves to prevent drying out—this is the dust mulch theory of cultivation, which has long been practiced in dry farming in the West.

TABLE 2.—*Monthly averages of the elements named*

Stations	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Agricultural College, N. Mex.:													
Temperature	42.1	46.2	53.0	60.5	69.1	78.2	80.4	78.6	72.5	61.5	49.3	42.1	61.1
Precipitation	0.31	0.44	0.33	0.20	0.27	0.53	1.72	1.70	1.30	0.72	0.56	0.49	8.57
Evaporation	2.866	4.498	7.407	9.373	11.095	11.906	11.148	9.786	8.092	5.934	3.629	2.520	88.254
Wind	1,496	1,885	2,452	2,385	1,654	1,394	1,412	1,042	1,053	1,179	1,318	1,443	18,713
Relative humidity	52	52	46	42	40	42	54	58	59	56	55	53	51
Clear days	19	15	18	20	21	20	12	13	18	21	20	18	215
Elephant Butte, N. Mex.:													
Temperature	40.4	45.3	52.4	59.1	67.3	76.8	79.3	77.5	71.2	60.4	48.4	39.4	59.8
Precipitation	0.29	0.32	0.46	0.46	0.31	0.78	2.15	2.26	1.36	0.67	0.40	0.60	10.06
Evaporation	2.775	4.486	7.754	10.444	13.430	14.481	12.219	10.828	9.071	7.755	4.321	3.053	100.617
Wind	2,774	2,953	3,912	4,071	3,956	3,344	2,909	2,551	2,724	3,339	2,642	2,855	38,030
Clear days	19	18	18	20	21	16	11	12	16	22	20	20	213
Lake Avalon, N. Mex.:													
Temperature	44.1	47.8	55.4	62.9	71.1	78.6	80.3	79.5	73.6	63.1	52.1	42.8	62.6
Precipitation	0.34	0.28	0.64	1.08	0.84	1.16	1.43	1.85	1.81	1.29	0.49	0.62	11.83
Evaporation	2.340	3.260	5.490	7.490	7.870	8.700	10.130	9.600	8.590	6.490	3.170	2.420	75.550
Clear days	20	18	21	21	20	19	17	17	19	20	21	19	232
Tucumcari Experiment Station, N. Mex.:													
Temperature	38.8	41.4	49.1	56.1	65.0	75.3	78.5	77.3	70.9	58.8	47.4	37.9	58.0
Precipitation	0.32	0.51	0.77	1.75	2.45	2.09	2.48	2.90	1.62	1.46	0.77	0.69	17.81
Evaporation				7.222	8.558	9.751	10.281	9.316	7.383	5.232			57.743
Wind	3,272	4,065	5,242	5,163	4,417	3,917	3,383	2,990	3,125	3,615	2,964	3,528	45,681
Clear days	24	20	22	18	21	20	19	19	21	24	21	22	251
Santa Fe Field, N. Mex.:													
Temperature	29	33	40	47	56	65	69	67	61	50	39	31	49
Precipitation	0.59	0.84	0.73	0.86	1.11	1.04	2.71	2.36	1.64	1.07	0.78	0.76	14.49
Evaporation	1.530	2.134	3.955	6.149	8.514	10.135	8.933	8.064	6.545	4.809	2.546	1.393	64.707
Wind	2,045	2,099	2,598	2,758	2,525	1,993	1,416	1,217	1,260	1,562	1,728	1,767	22,968
Relative humidity	60	59	50	44	39	38	52	54	51	50	54	60	50
Clear days	18	14	15	15	15	17	10	11	17	20	19	18	190
Spur, Tex.:													
Temperature	40.5	44.3	50.6	60.3	69.3	78.4	81.9	81.0	73.4	62.3	51.5	41.6	61.3
Precipitation	0.28	0.56	1.04	2.58	3.15	2.53	1.54	2.37	2.74	2.97	1.04	0.86	21.66
Evaporation	2.789	3.535	4.817	5.483	6.662	8.684	9.330	7.876	5.590	4.378	3.419	2.339	64.902
Wind	3,974	4,131	4,797	4,222	4,277	4,051	3,381	2,847	2,911	3,115	3,793	4,133	45,632
Clear days													
Hills Ranch, Tex.:													
Temperature	47.7	52.7	59.4	67.0	73.6	81.2	83.6	83.5	77.9	68.1	57.6	50.3	66.9
Precipitation	2.28	2.10	1.88	4.06	4.26	3.27	2.47	1.16	4.12	4.36	2.23	1.64	33.83
Evaporation	2.467	3.429	5.293	6.005	6.805	7.952	8.968	8.716	6.360	4.956	3.176	2.438	66.565
Wind	2,294	2,356	2,544	1,821	1,171	914	970	930	909	1,201	1,455	2,132	18,694
Clear days													
Beeville, Tex.:													
Temperature	55.3	57.1	65.0	70.6	76.8	82.2	84.1	85.0	84.4	82.6	73.2	59.6	70.6
Precipitation	1.25	1.97	1.88	2.38	3.24	3.02	2.65	2.42	3.65	2.55	2.12	1.98	29.11
Evaporation	2.691	3.258	4.260	4.791	6.214	7.354	8.141	8.143	5.889	4.721	3.056	2.165	60.683
Wind	5,300	5,401	6,277	5,701	4,770	4,190	4,511	3,897	3,473	3,712	4,148	4,600	55,980
Clear days													
Lees Ferry, Ariz.:													
Temperature	33.6	43.6	50.5	59.5	71.7	80.0	86.1	82.6	74.0	60.6	47.4	37.0	60.5
Precipitation	0.13	0.25	0.42	0.83	0.19	0.09	0.49	0.93	0.81	0.48	0.34	0.58	5.59
Evaporation	1.741	3.524	5.871	7.160	11.697	13.697	13.698	11.325	8.850	6.288	3.097	1.912	88.860
Wind	1,038	1,268	2,348	1,853	1,995	1,768	1,629	1,431	1,297	1,301	999	1,101	18,028
Clear days													
Roosevelt Dam, Ariz.:													
Temperature	47.8	51.9	57.5	64.9	74.0	83.8	88.0	86.1	80.0	68.2	57.5	48.1	67.3
Precipitation	2.41	2.14	2.01	0.97	0.31	0.43	1.78	2.27	1.00	1.22	1.37	2.08	17.99
Evaporation	2.291	3.104	5.326	7.320	10.367	12.670	12.335	10.561	8.596	5.780	3.520	2.134	84.004
Wind	1,008	1,034	1,361	1,336	1,346	1,206	1,476	1,136	1,033	887	734	862	13,419
Clear days													
Mesa Experiment Station, Ariz.:													
Temperature	50.6	53.9	58.7	65.2	72.7	82.8	87.4	86.0	80.1	68.7	57.6	50.1	67.9
Precipitation	1.04	0.85	0.86	0.40	0.12	0.13	1.22	1.19	0.64	0.53	0.84	1.08	8.90
Evaporation	2.783	3.675	5.740	7.783	10.273	11.172	10.547	8.290	6.387	4.729	3.354	2.623	77.356
Wind	1,209	1,253	1,464	1,496	1,359	1,168	1,110	840	642	708	1,007	1,235	13,491
Clear days													
Wilcox, Ariz.:													
Temperature	40.4	44.2	47.9	54.4	62.6	72.4	76.5	73.6	69.1	57.9	47.9	41.3	57.4
Precipitation	0.85	0.58	0.77	0.21	0.35	0.51	2.54	2.48	0.88	0.52	0.87	0.66	11.22
Evaporation	3.586	4.726	7.286	10.101	11.241	12.220	10.639	9.026	8.103	6.695	4.666	3.412	91.701
Wind	2,732	2,597	3,131	3,320	2,583	1,967	1,836	1,376	1,640	1,694	2,312	2,536	27,724
Clear days													
Yuma Citrus Station, Ariz.:													
Temperature	53.3	60.2	62.6	68.0	77.0	85.0	88.3	90.6	84.2	72.2	61.9	54.7	71.5
Precipitation	0.32	0.05	0.13	0.21	0.03	0.00	0.14	0.97	1.26	0.24	0.16	1.03	4.54
Evaporation	4.214	5.921	8.272	10.620	14.107	15.886	17.588	15.279	11.938	8.442	5.538	3.803	121.608
Wind	1,340	1,625	2,114	2,335	2,245	2,135	2,441	2,096	1,598	1,274	1,255	1,403	21,861
Clear days													
Yuma Evaporation Station, Ariz.:													
Temperature	50.9	55.3	58.8	63.8	69.9	79.3	83.2	85.5	80.4	68.4	58.1	52.3	67.5
Precipitation	0.54	0.17	0.29	0.10	0.03	0.02	0.18	0.43	0.50	0.34	0.14	0.49	3.23
Evaporation	3.091	3.886	5.723	7.254	8.236	8.907	10.243	9.958	7.850	5.394	3.396	2.619	76.557
Wind	1,012	1,010	1,282	1,325	902	636	898	1,098	865	742	760	903	11,433
Clear days													